Direct Impulse Measurements of Ablation Processes from Laser-Surface Interactions

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A torsional impulse balance has been developed as a new diagnostic tool to study fundamental processes in laser-surface interactions. Of particular interest are the forces due to processes of laser ablation. With respect to the transfer of momentum, direct measurements of the transient forces can lead to a better understanding and characterization of the efficiency of the impulse that is possible under different configurations. The impulse balance has been designed and tested with a robust calibration system to measure impulsive forces with resolution as low as several nano-Newton-seconds. Initial results of impulses due to ablation from an Nd:YAG laser (532nm) on various metals and other materials are presented.

I. Introduction

Significant work has been done in the past to understand and model the fundamental processes involved in laser-surface interactions for a wide range of materials and lasers.[1],[2] Of particular interest are the impulsive forces produced by laser ablation processes. Many techniques exist to measure the amount of material ablated from a surface and the velocity at which it is ejected, such as time-of flight mass spectrometry. With respect to momentum transfer, direct measurements of the forces can lead to a better understanding and characterization of the efficiency of the impulse that is produced under different conditions. Such measurements can be achieved with an impulse balance with a highly accurate calibration method, such as the one described here. From a propulsive perspective, a common measure of propulsive efficiency is the specific impulse[3], I_{sp}, given by

$$I_{sp} = \frac{1}{M_p g_o} \int_{t=0}^{t=t'} F(t)dt \qquad \text{Equation 1}$$

where F(t) is the time dependent force produced by the thruster, t' is the thruster's pulse duration, and M_p is the total mass of the propellant lost in the pulse, and g_o is the Earth's gravitational constant. From Eq. (1), it can be seen that details of the impulse delivery in the integral are important for thruster efficiency. As such the direct measurement of the force can be a very useful tool.

There are a number of applications of current interest that require the investigation of the propulsive forces from laser-produced photons interacting with surfaces. Two of these applications are laser propulsion and the development of pressure-driven microdevices[4]. Laser propulsion systems have been extensively discussed since the early 1970s.[5] Laser propulsion concepts range from alternative launch solutions to on-orbit maneuvering or attitude control systems for spacecraft, and have employed an equally diverse range of momentum transfer mechanisms including ablation, shock wave generation[6], and even photon pressure[7]. The lasers used in these applications also vary in their characteristics from continuous to pulsed beams with powers ranging as low as a few watts to as high as megawatts. Some thruster systems, such as the micro-Laser Plasma Thruster by Phipps et al[8], are being developed using small low-power solid state lasers and stored ablative propellants to generate impulses.

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14. ABSTRACT
A torsional impulse balance has been developed as a new diagnostic tool to study fundamental processes in laser-surface interactions. Of particular interest are the forces due to processes of laser ablation. With respect to the transfer of momentum, direct measurements of the transient forces can lead to a better understanding and characterization of the efficiency of the impulse that is possible under different configurations. The impulse balance has been designed and tested with a robust calibration system to measure impulsive forces with resolution as low as several nano-Newton-seconds. Initial results of impulses due to ablation from an Nd:YAG laser (532nm) on various metals and other materials are presented.

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Within the scope of laser ablation, there is interest in studying a wide variety of physical processes that more precisely include desorption, vaporization, ablation, sputtering, etc. The scope of the current study will examine the conditions under which these physical processes occur and the parameters that control them. Experimental tests were conducted using a variety of metal and non-metal targets. There were two main goals in this experimental study. The first goal was the development of an impulse balance capable of obtaining time accurate force measurements with 1 nNs resolution. This proof of principle was described by D'Souza et al[9] for time accurate force measurements on the order of 0.1-1 sec and paves the way for improvements to provide time resolution on the order of microseconds. The second goal was to demonstrate the impulse balance's ability to measure ablation forces from the interaction of a laser beam with a sample material surface, and to acquire a broad range of measurements that demonstrate the dependence of laser-surface processes on parameters such as pulse energy, fluence, wavelength, and pulsewidth. This experimental work is ongoing. The initial results presented in this paper examine the efficiency of impulse generation for several materials with a Nd:YAG laser at 532nm for a broad range of energies. Follow-on studies are intended to complete this parametric study.

II. Experimental Setup

This study involves the use of a nano-Newton-second Impulse Balance System (NIBS)[10] as a diagnostic tools for the accurate measurement of individual impulse bits for micro-device actuation and laser propulsion systems. The current NIBS has been able to resolve impulses as low as 7 nano-Newton-seconds, and as high as 150 micro-Newton-seconds, which has provided an acceptable range to study a number of the ablative processes. The impulse balance can also be modified and recalibrated to provide an extended range, if needed. The current version of the NIBS is based upon a torsional thrust stand described in previous work.[11] The NIBS design has been modified to allow for very low impulse measurements, which could not be attained by previous versions of the stand. An electrostatic comb force calibration technique described by Selden and Ketsdever[12] has been employed to accurately calibrate the system for impulses.

The NIBS is installed in a 41 cm diameter x 122 cm long, stainless steel vacuum chamber fitted with a 450 L/sec turbomolecular pump capable of maintaining pressures of approximately 10^{-6} Torr. The motion of the NIBS is measured using a linear variable differential transducer (LVDT), which is connected to an 18-bit data acquisition system capable of sampling at up to 500KS/s. A simple low-pass filter is used on the LVDT signal to minimize electrical noise. The analog filtering serves to complement the signal processing techniques employed, which further reduce the noise in the experimental data prior to analysis.

For calibration of the system, impulse delivery to the NIBS is accomplished by supplying a potential difference to the Electrostatic Force Calibration System (EFCS). The EFCS consisted of an aluminum comb assembly[12] with one side of the EFCS assembly attached directly to the NIBS. As shown in the experimental setup in Figure 1, the power supply for the EFCS is attached to a pulse generator capable of delivering ±3500 V with a 20 ns rise time and a variable DC pulse width (minimum of 60 ns). The output of the pulse generator is sent directly to the EFCS assembly in the chamber through a high voltage vacuum feedthrough and is monitored by the 18-bit data acquisition (DAQ) system. The applied (and monitored) voltage to the EFCS is used to calculate the actual impulse applied to the NIBS.[12] Calibration of the NIBS is a critical element of this study. Through repeated calibration tests in the actual experimental test configuration, calibration curves can be derived which enable the unknown impulse from the laser-surface interactions to be resolved. Extensive testing on the NIBS has been conducted, such that the application of a variety of known impulses from the EFCS of different magnitudes and pulsewidths demonstrate the stability and repeatability of the NIBS. The actual force produced by the EFCS was also independently calibrated by the microbalance method described by Selden and Ketsdever.[12] The error for a given applied force was found to be less than 2%. From these tests, a process has been developed to characterize the impulse balance well under any configuration.

The general setup for the preliminary laser-surface interaction experiments is also shown in Figure 1. A Nd:YAG laser is used with a wavelength of 532 nm and a variable pulse energy up to 300 mJ. The pulse width of the laser is approximately 3-5 nanoseconds. The laser beam passes directly into the vacuum chamber through a quartz window.

The beam illuminates the ablation target material secured to the NIBS. A number of parameters are controllable, such as the spot size and pulse energy, allowing the control of the energy density on the surface. To measure the shot-by-shot variation of the laser energy, a small percentage of the laser beam is sampled using a beam splitter and a power / energy meter.

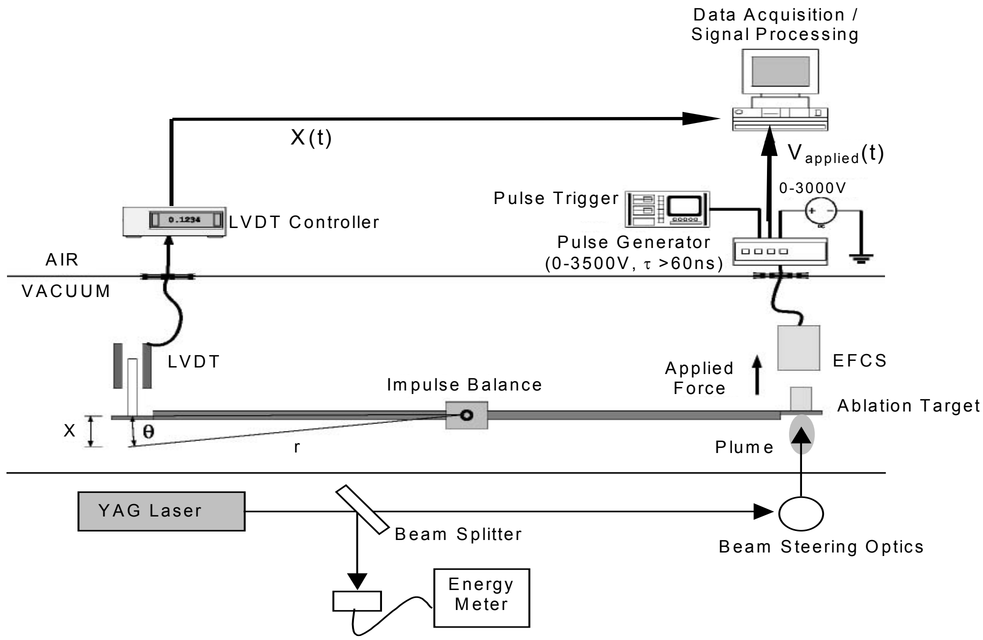


Figure 1. Schematic of NIBS experimental setup and TRIM process for obtaining the derived and applied forces imparted to the impulse balance as a function of time.

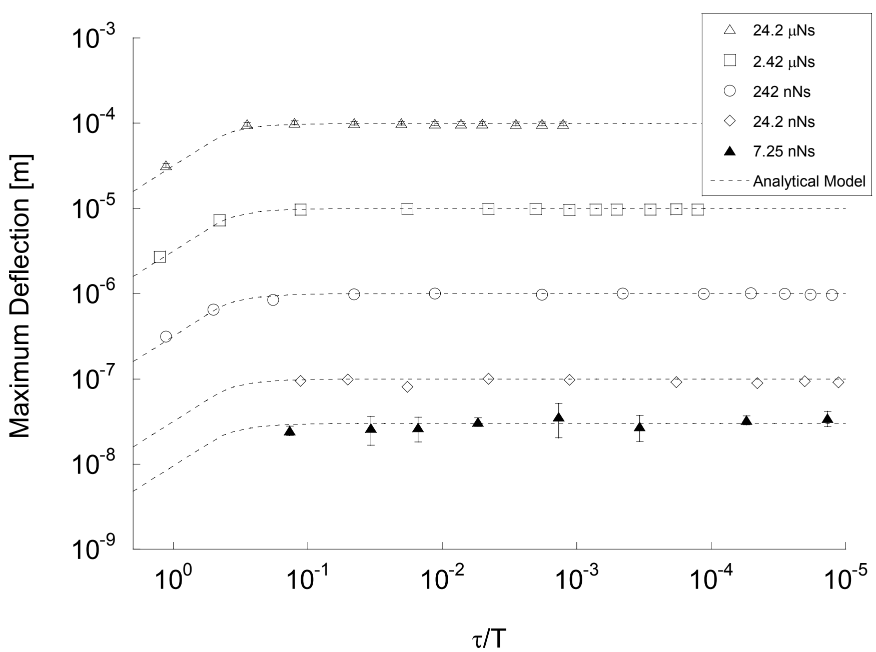


Figure 2. NIBS maximum deflection as a function of normalized impulse pulsewidth compared to the analytical model results. For t « T, the maximum deflection is constant . The data points represent experimental measurements with error bars showing the standard deviation of at least 10 repeated tests.

Typically, impulse balances are operated using the assumption that the maximum deflection is linearly dependent on the delivered impulse.[13],[14] The assumption is only strictly valid for laser pulsewidths (τ_i) much less than the natural period (T) of the balance. An analytical model was developed to examine the impulse balance characteristics. Figure 2 shows a comparison of the analytical model with experimental data demonstrating the maximum NIBS deflection as a function of τ_i / T for various total impulses. The dashed lines represent the theoretical fit using the experimentally derived thrust stand characteristics. As seen in Figure 2 for $\tau_i > 0.1$ T, the direct correlation between the maximum balance displacement and the delivered impulse is no longer valid. For , $\tau_i \ll$ T, the maximum deflection has a linear relationship with the total impulse. Figure 3 shows the NIBS maximum linear deflection as a function of applied impulse. The analytical model is in good agreement with the experimental data as shown in Figure 3. The analytical model captures not only the trend of the experimental data, but is also in excellent agreement with the magnitude of the data. For ablation processes, the timescale of the effect will typically be much smaller than the period of the balance. As such, the traditional maximum deflection analysis will be sufficient to study ablation effects.

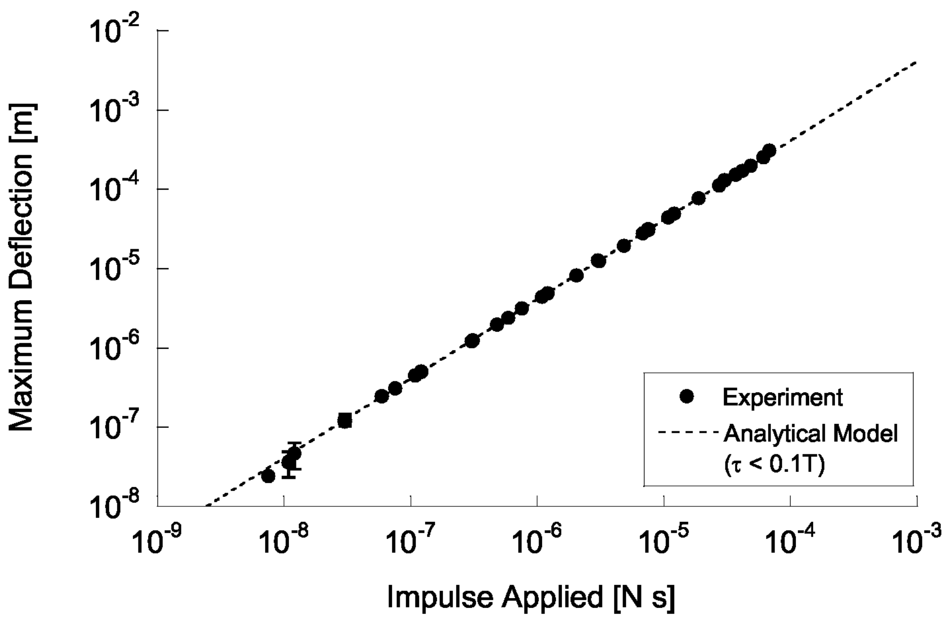


Figure 3. Comparison of maximum deflection versus applied impulse of the analytical model and experimental deflection data. Error bars represent the standard deviation of at least 10 repeated tests, and are typically smaller than the symbol used.

III. Results

As has been mentioned previously, the experimental testing of the laser-surface interactions with the current setup is still in its early stages. It is expected that besides the basic thrust measurements, other techniques may be used in the future to corroborate the results. Much work has already been done in the modeling of many of the processes of interest[2]. These will serve as a comparison for the validation of the experimental methods used. Initial proof of concept studies using the NIBS as a diagnostic tool for the ablation of surface materials being irradiated by laser beams have focused on using commonly available materials, including aluminum (plain and anodized), steel, stainless steel, copper, Teflon (virgin and mechanical grade), Delrin (natural and black), Buna-N and Viton.

As described in the previous section, a Nd:YAG laser is used with a wavelength of 532 nm and a variable pulse energy up to 300 mJ. The pulse width of the laser is approximately 3-5 nanoseconds (ns). For the calculation of Intensity (in W/cm^2), the average pulsewidth of 4 ns is used. For these tests at 532 nm, a spot diameter of 1.2 mm ± 0.1mm was achieved by a single bi-convex lens. The spot size was verified using laser burn-paper. Differences in

laser pulse parameters from experiments and models in the literature make direct quantitative comparisons difficult. Fortunately, the general trends are maintained and can be qualitatively compared to existing models and other experimental measurements.

Based on the models described by Phipps, et al.[2], the figure of merit to use for comparing such laser ablation interactions is the mechanical or momentum coupling coefficient Cm:

$$C_m = P_a / I = \mathcal{J} / W_L \qquad \text{Equation 2}$$

where P_a is the ablation pressure, I is the incident laser intensity, $\mathcal{J}$ is the impulse to the target, and W_L is the laser energy. As impulse and the laser energy can both be measured accurately with the experimental system, accurate C_m values can be derived.

As shown in Figure 4, each of the metals behave in generally the same fashion. The generated impulses increase as the fluence (and pulse energy) increase. However, the trend is not linear. Due to shielding by the ejected plasma, increases in incident energy do not result in proportional increases in impulse. This shielding effect is a result of the plasma forming faster than the entire pulsewidth of the laser. As a result the incident light partially interacts with the plasma and does not completely arrive at the target surface. To examine the efficiency of the laser pulses, we can examine the relationship between C_m and intensity, as shown in Figure 5. As predicted in Phipps models[2], the impulse efficiency rapidly reach a maximum once the ablation thresholds are surpassed, and decline with increasing intensity. It can be seen that as intensity is increased, plasma formation increases and has a greater shielding effect. Also, for pulsewidths on the order of 3-5 ns, the intensity for which C_m is maximized should occur between 10^8 and 10^9 W/cm^2. Of particular note for these metals, the ablation thresholds for aluminum, steel and stainless steel are relatively equal. Whereas, copper requires about 3 times the fluence to reach its ablation threshold.

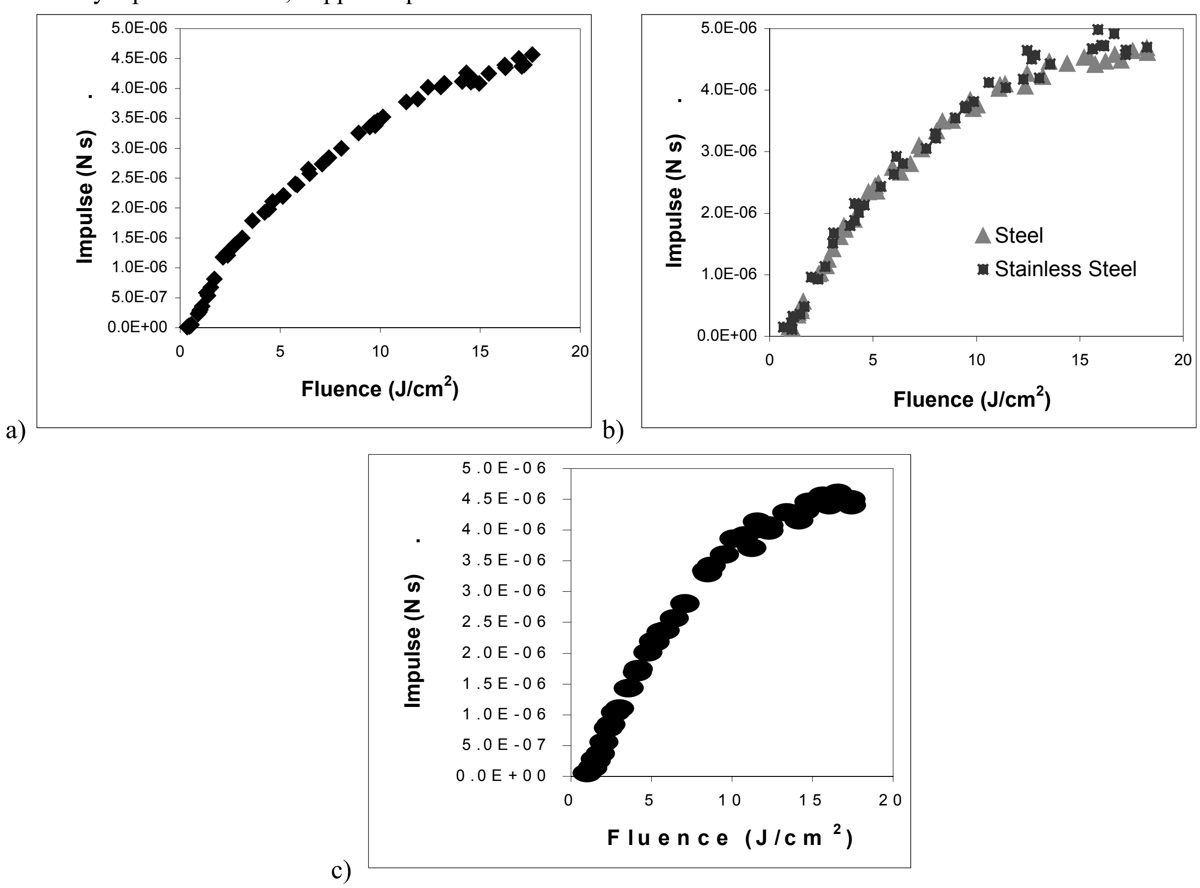


Figure 4. Impulses from ablation of metals using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm. The figures represent results for (a) aluminum, (b) steel and stainless steel, and (c) copper.

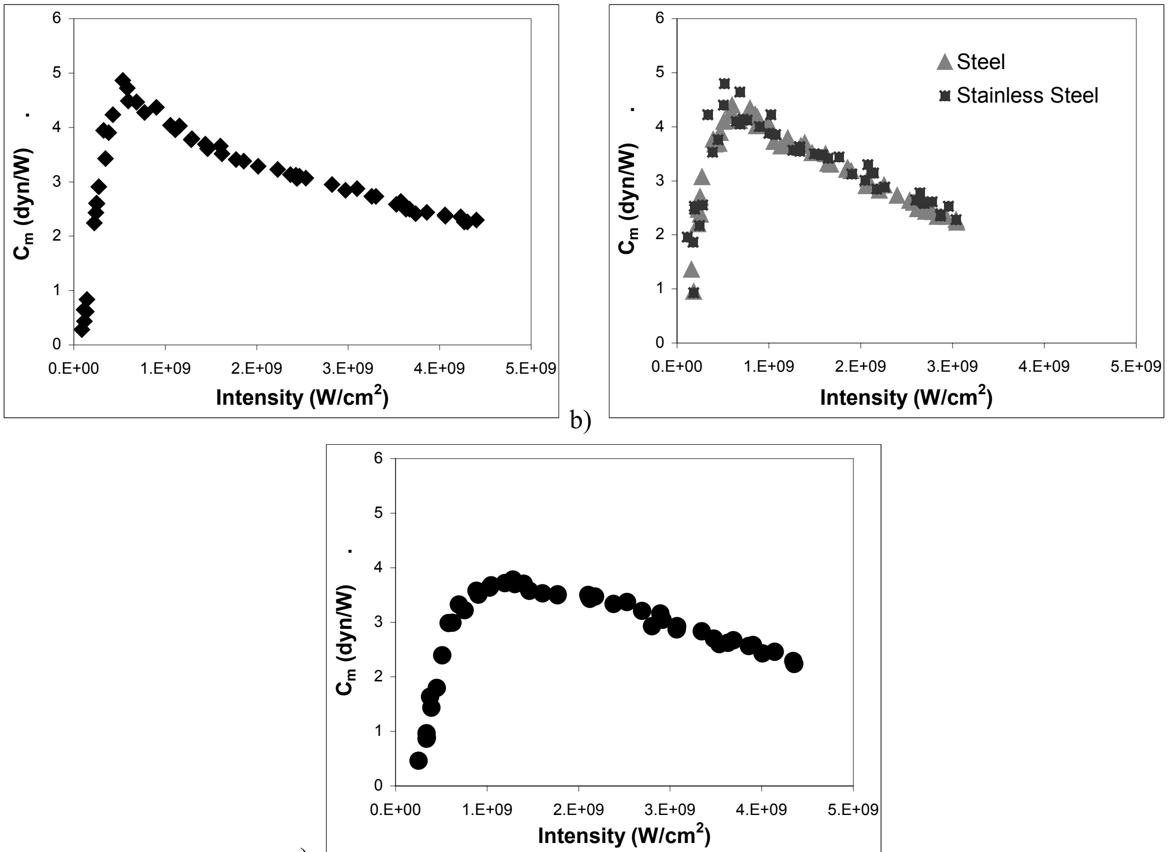


Figure 5. Momentum coupling term C_m as a function of intensity of the incident laser pulse for a variety metals using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm. The figures represent results for (a) aluminum, (b) steel and stainless steel, (c) copper.

Also of interest is the reaction of the anodized aluminum. It can be seen in Figure 6 that the anodized material experiences much higher impulses and efficiencies than the other metals for similar fluence levels. However, unlike the other metals, the impulse for the anodized material does not continuously increase as the fluence is increased. Eventually, a point is reached where additional energy decreases the overall impulses. The anodized surface provides a layer of material that is more likely to absorb the incident photons than an untreated aluminum material. The higher impulses are most likely due to the loss of bulk anodized material. The anodized layer was approximately 38±13 μm in thickness. Successive shots on the same target site tend to reveal that such high impulses are only to be expected for the anodized layer. Once the layer is ejected, the material behaves more like the plain aluminum underneath. With each shot on the anodized aluminum surface, less potential ablatant remains for the subsequent pulses. Likewise, as the fluence becomes larger more surface material can be removed in a single shot, to the point where the entire anodized layer is removed for the target site. Increasing the fluences further simply result in lower efficiency as the pulse is also interacting with the plain aluminum material.

The next set of materials examined were natural and black Delrin. The black Delrin was doped with a coloring process making the material opaque, whereas the natural Delrin was slightly translucent. From Figure 7, it can be seen that the black Delrin tended to ablate at much lower fluences. More of the incident energy was being absorbed at lower fluences. However, as the fluences increase the black Delrin quickly maximizes its efficiency, to the point where additional incident energy results in lower impulses. This would indicate that the plasma formation reaches a point where it can almost completely shield additional incident photons. In the case of the natural Delrin, the material requires higher fluences to reach its ablation threshold. Also, the incident photons are penetrating much

deeper into the material. The result is that higher overall impulses can be achieved, even though the efficiency is not as good as the blackened material.

a) b)

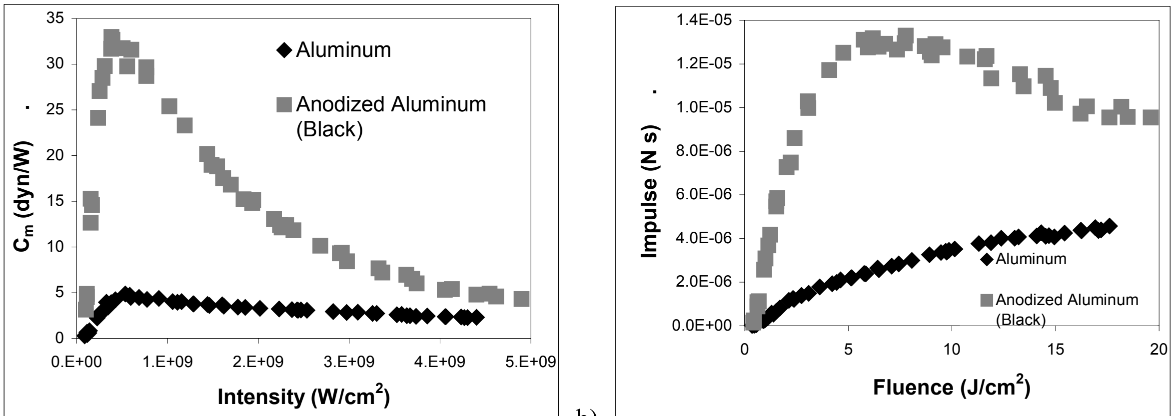


Figure 6. (a) Momentum coupling term C_m as a function of intensity of the incident laser pulse for black anodized aluminum as compared to plain aluminum. (b) Impulses from ablation of black anodized aluminum using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm.

a) b)

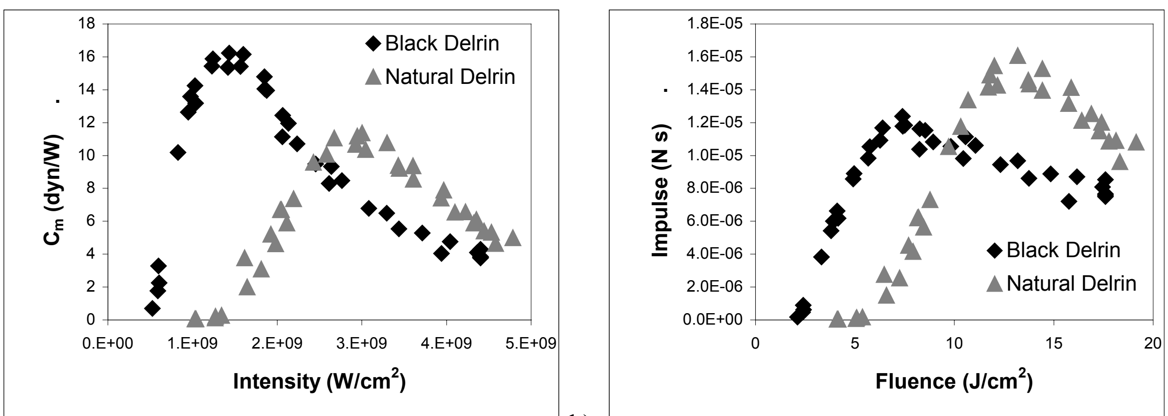
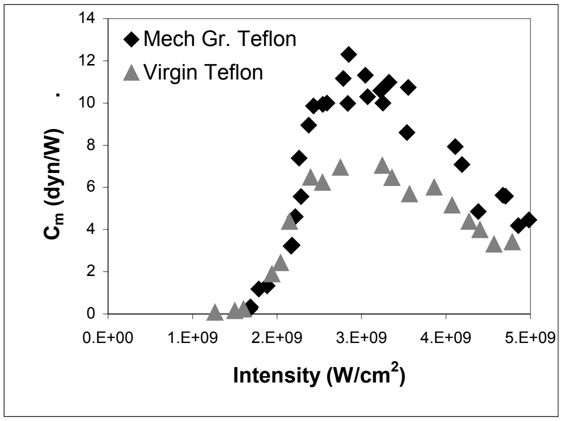


Figure 7. (a) Momentum coupling term C_m as a function of intensity of the incident laser pulse for black and natural Delrin. (b) Impulses from ablation of black and natural Delrin using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm.

Another common ablatant used in microthrusters is Teflon. For these studies, two grades of Teflon were chosen, a mechanical grade and virgin Teflon as shown in Figure 8. Overall, the mechanical grade had higher impulses and efficiencies. Both had roughly the same ablation threshold. Of all the materials tested, the mechanical grade Teflon produced the highest impulses for similar fluence rates. Similar to the Delrin, it was found that increasing the fluence beyond a certain point actually resulted in a decrease in the impulse generated. Such a limit is of particular interest when looking to optimize a thruster design which utilizes Teflon as its fuel source.

The final set of materials examined in this initial phase of testing were the elastomer materials, Viton and Buna-N as shown in Figure 9. Originally these materials were chosen for comparison with figures from the literature[2]. However, due to inconsistencies in pulsewidth and wavelength a fair comparison cannot really be made with this set. It is interesting to note, however, that these materials have very low ablation thresholds and the impulse seems to plateau quite quickly. At the low range of fluences, these materials provide excellent efficiency.



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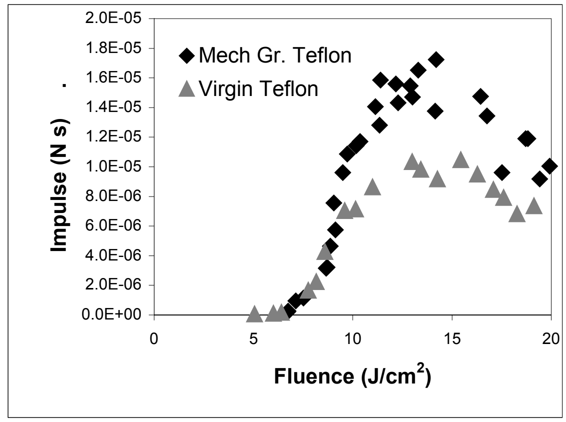
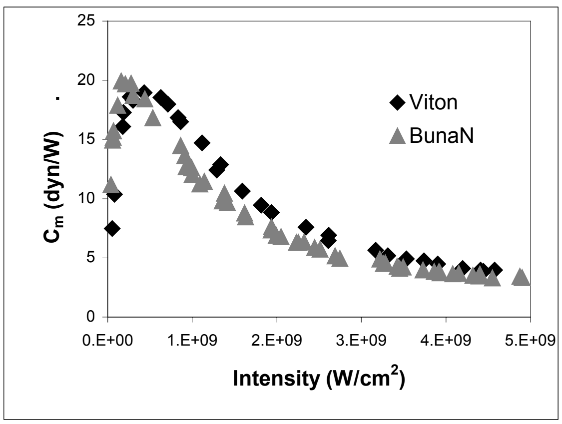
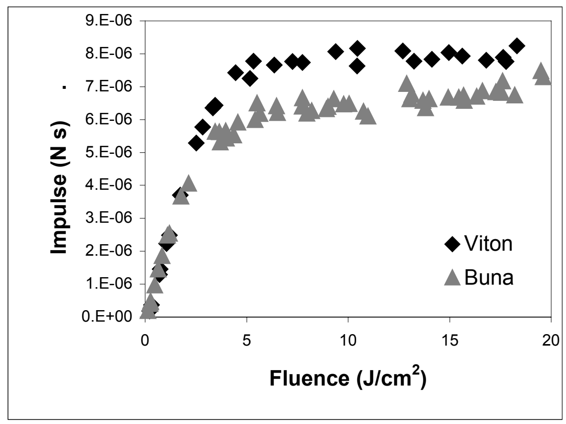


b)

Figure 8. (a) Momentum coupling term C_m as a function of intensity of the incident laser pulse for virgin and mechanical grade Teflon. (b) Impulses from ablation of virgin and mechanical grade Teflon using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm.



a)



b)

Figure 9. (a) Momentum coupling term C_m as a function of intensity of the incident laser pulse for Viton and Buna-N. (b) Impulses from ablation of Viton and Buna-N using a Nd:YAG laser at 532nm with a spot diameter of 1.2mm.

IV. Conclusions

The results from these initial ablation tests reveal a number of interesting characteristics about each material, which can help to assess their feasibility for use in applications such as laser propulsion. When considering the metals as ablatant sources the overall efficiencies as represented by C_m are quite low in comparison to the polymers. Only the anodized aluminum provided relative large impulses as long as the anodized layer remained.

Considering Teflon and Delrin are already being used in a number of laser propulsion devices[15],[16], it is not suprising to see that these materials produce significantly higher impulses and with greater efficiency than the other materials tested. Even Delrin and the elastomers reached relatively high efficiencies. The critical factor in using any of these materials efficiently is to find the fluence at which the impulse is optimized. Depending on the laser source and the fluence produced, an appropriate ablatant could be chosen. At lower fluences around 5J/cm^2, Viton or Buna-N might be the most appropriate ablatant, as Teflon barely reacts. At higher fluences like 10J/cm^2, Teflon or Delrin become more attractive options. Of course, these numbers may only be valid for the testing configuration. One would expect the ablation characteristics for each material to be somewhat dependent on laser parameters such as intensity, wavelength, and pulsewidth. It is for this reason, that a more thorough parametric study would be valuable.

In summary, a diagnostic tool capable of measuring impulses as low as 7 nNs resolution has been developed. A proof of principle demonstration of the NIBS ability to provide accurate impulse measurements has been completed. The ablation results demonstrate the feasibility to effectively measure the impulses due to laser-surface interactions, although system improvements are required for accurate time resolved data for laser ablation mechanisms. Through the variation of parameters such as wavelength, spot size, fluence, material and ambient environment, a robust data set can be collected to investigate a range of laser-surface interactions and the transition between them. Such a dataset could be extremely useful in validating the development of laser-surface interaction models and provide valuable insight into the development of laser-propulsion devices.

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